REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
Aug – Sep 1992

2. REPORT TYPE
Technical Paper

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
(See attached)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
(See attached)

5d. PROJECT NUMBER
3058

5e. TASK NUMBER
00C4

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)
(See attached)

8. PERFORMING ORGANIZATION REPORT NUMBER
IAF-92-0617

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
PL-TP-93-3052

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

12. DISTRIBUTION / AVAILABILITY STATEMENT
(See attached)

13. SUPPLEMENTARY NOTES
These are technical papers, presentations that have been presented by AFRL/PRS from 1994.
43rd Congress of the International Astronautical Federation, 28 Aug – 5 Sep 1992, Washington, DC

14. ABSTRACT (maximum 200 words)
(See attached)

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	SAR		Kenette Gfeller or Leilani Richardson

19b. TELEPHONE NUMBER *(include area code)*
DSN 525-5015 or 525-5016

PL-TP-93-3052

WORLD SPACE CONGRESS 1992™

IAF-92-0617

Arcjet Thruster Experimental Facility at the United States Air Force Phillips Laboratory

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43rd CONGRESS OF THE INTERNATIONAL ASTRONAUTICAL FEDERATION
August 28-September 5, 1992/Washington, DC

ARCJET THRUSTER EXPERIMENTAL FACILITY AT THE UNITED STATES AIR FORCE PHILLIPS LABORATORY

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Abstract

The paper discusses the unique design and construction of the vacuum, cooling, power and propellant systems of the arcjet experimental facility. An overview of current and future arcjet thruster development is presented. The thrusters discussed are 10-30 kilowatts in power, use ammonia or hydrogen as propellant, and are either radiation cooled or regeneratively cooled. Extensive calibrations have been conducted on the mass flow system. The uncertainties have been quantified over a large range of mass flows and propellants. The vacuum system is quantified for actual pumping capability. Power system has been analyzed for voltage and current output stability and ripple. The thruster's Electromagnetic Interference (EMI) has been characterized to support a space experiment with arcjets. This is the only facility in the world developing and characterizing high power arcjets for the use in orbit transfer.

Introduction

United States Air Force (USAF) requirements for improved orbit transfer and station keeping capabilities have resulted in the development of electric propulsion systems. The anticipated performance improvements of electric thrusters over chemical thrusters allows either the use of smaller launch vehicles or larger payload delivered to geosynchronous and other high altitude orbits. The electric propulsion technology being developed for near term applications is the arcjet. The arcjet's high specific impulse (800 - 1500 seconds) make it a candidate for future missions. This has spurred the construction of an arcjet experimental facility at the Phillips Laboratory, Edwards Air Force Base, California.

The USAF has been constructing an electric propulsion (EP) laboratory for the past three years at Edward Air Force Base in California. The facility is part of the Air Force's Phillips Laboratory which has as its prime mission to develop space and missile technology. The EP laboratory was constructed in a 3800 square foot concrete building[1]. The arcjet facility construction began in 1989 and was completed in 1992, with the first firing of an arcjet on July 22, 1992. The arcjet facility, built with in-house resources, was designed to meet present and future need for arcjet thruster development.

The facility was designed to fire arcjets, which are the most technologically mature high power electric thrusters. The arcjet is an electrothermal rocket, in which an electric arc is used to heat a gas (propellant). Hot propellant is accelerated by expansion in a conventional nozzle, which converts thermal energy into unidirectional velocity to produce thrust[2]. Electric heating creates temperatures thousands of degrees Celsius hotter than by chemical combustion. The higher temperature produces a specific impulse of 850-1500 seconds, which means less propellant to perform a space mission[3,4].

Facility Description

The facility is designed to run up to a 100 kW thrusters at a mass flow of one gram per second (g/s) or two thrusters that together reach that power and mass flow, while maintaining a vacuum chamber pressure of 80 millitorr. There are 3 pump systems planned, one is operational, the other in place, and the third is to be procured. All pumps are located outside the building and connected via an 18 inch diameter duct to chambers 1 and 4 (see fig. 1). Chamber 2 is connected to the pumps via an 8 inch diameter vacuum duct. Valves isolate each chamber, allowing chambers to be operated simultaneously or singularly[5].

The pumping system which evacuates one g/s of ammonia at over 500 degree's C consists of 3

sets of mechanical vacuum pump trains (see fig. 2). A Stoke 412 mechanical pump with a speed of 142 lps (300 CFM) roughs out the chamber and ducts. Once the pressure is below 25 mm of Hg, the second stage, a Roots 615 booster pumps at a pump speed of 615 lps (1300 CFM). Finally the pressure reaches 1 mm of Hg and the Roots 1845 HVB high vacuum booster pumps at 9160 lps (19400 CFM). The pumps must turn on in stages, otherwise differences in pump speed would over pressure the lower speed pumps and cancel their effectiveness.

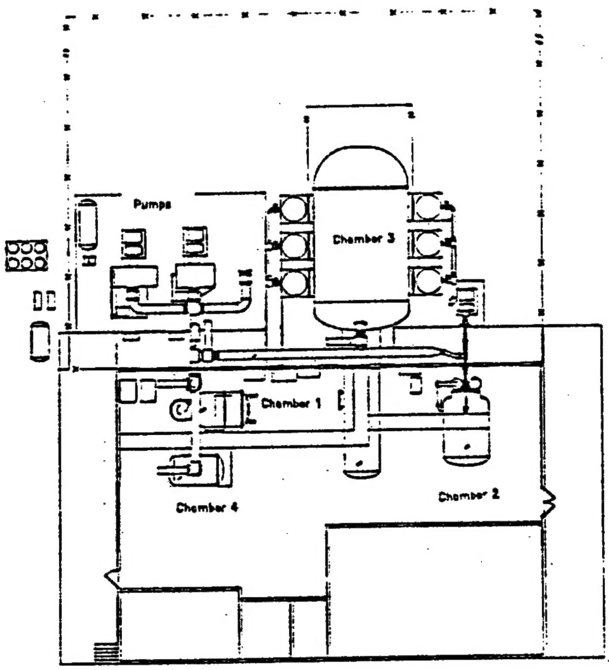

Figure 1
Facility Layout

The facility must remove the heat of the thruster and maintain vacuum system cooling water at a constant temperature throughout the temperature extremes experienced at Edwards AFB in the Mojave desert (12 to 43 deg. C [10-110 F]). A 50 ton (176 kW) water chiller supplies chilled water for the cooling panels inside the chamber and water cooling for the pump system. A two water tank cooling system has been constructed (fig. 3), enabling the chamber cooling panels to be at a colder temperature than the water to the vacuum pumps. A fully automated Trane water chiller model CGAD-M-3 with a capacity of 176 kW provides water in tank #1 at 10 deg. C (50 F). Water from tank #1 circulates through all the chamber cooling panels removing the arcjets heat. Water from tank #1 is mixed into tank #2, maintaining the temperature needed by the pumps, between 21-27 deg. C (70-80 F) all year round; thus the water in tank #2 must be cooled in the summer and heated in the winter. If the water is below 15 deg. C (60 F), the vacuum pump oil will be too viscous and will prevent pump start up. Four 16 kilowatt heaters located in tank #2 heat the water in about a half an hour. Thermocouples on tank #2 and a computerized control system maintain the proper heating and cooling to keep the desired temperature range.

The required arcjet power of 100 kilowatts is provided by two Linde (L-TEC), PHC-601 plasma welding supplies that can supply 120 kilowatts of total power. Presently, each power supply is connected to a separate chamber giving 60 kW to each. The input power is 600 amps, 480 volts, 3 phase giving an output of 600 amps, continuously and 750 amps, for 30 minutes at 250 voltage DC. The power supplies are connected through four nought multistrand copper welding cable rated at 300 Amps maximum, which provides sufficient current to run a 30 kW thruster. A ballast resistor is connected in series with the thruster on the anode side, which guaranties that there will be a load on the power supply even if the thruster has a direct short. The ballast resistor is a Milwaukee Resistor Corp, 0.224 ohms 100 kW resistor and has been wired to provide two 0.112 ohms 50 kW resistors, one for each supply. Voltage is measured by a 100 to 1 voltage divider across the thruster located at the power feed into the vacuum chamber. The current is measure through a 10 to 1 voltage divider by using the ballast resistor as a shunt. The power supplies generate a 10 percent ripple (see fig. 4).

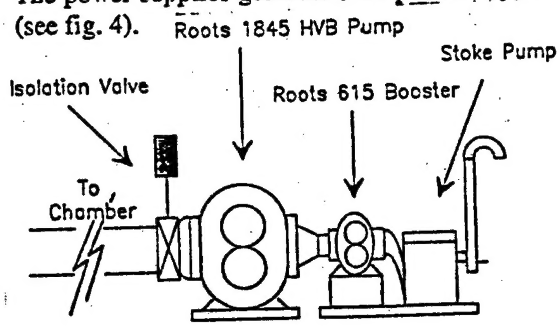

Figure 2
Pump System

A small propellant system was constructed to perform initial arcjet experiments using argon and ammonia. A permanent propellent system capable of providing gaseous ammonia for hundreds of hours of arcjet testing is under design and construction. The small system (see fig. 5) contains a 33 liter bottle of anhydrous ammonia liquid and a high pressure cylinder of commercial grade argon. The arcjet is started on argon and then switched to ammonia, since the arcjet will not start on ammonia without a high voltage spike provided by a starter circuit. Relief valves were connected to a common vent line, that opens to air several meters away from the control valves, to prevent venting of ammonia in the vicinity of the operator. There was concern about the possible hazard associated with an ammonia leak, therefore the propellant system was located outside except for a quarter inch propellant line that enters the building. Anhydrous ammonia forms a weak base when in contact with water, thus causing skin, eye, and lung irritation, which can cause asphyxiation[6]. Future plans include a small hydrogen propellant system to fire a 2 Kw thruster.

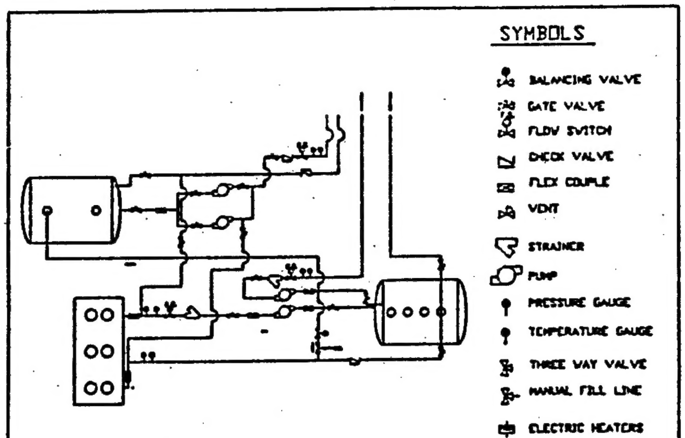

Figure 3
Cooling System

Mass Flow Measurement

The propellant flow rate is difficult to measure due to the low rate, usually 0.4 lpm; the flow rate is measured using a Micro Motion model D6 mass flow meter. Achieving values of mass flow that are traceable to standard is very difficult and a calibration procedure has been established that uses National Bureau of Standard (NBS) traceable measurements[7].

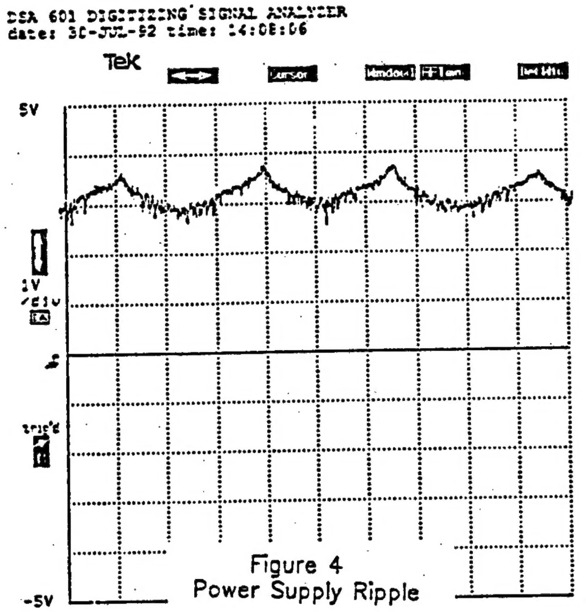

Figure 4
Power Supply Ripple

The calibration procedure consisted of accurately weighing a one-liter bottle of compressed gas before and after its contents were discharged through the flowmeter. By dividing the net mass lost by the time over which the discharge took place, an accurate determination could be made of the average mass flow rate. Comparing this measured flow rate to the flowmeter's output enables a calibration curve to be generated. Several different gases used determine the flowmeters sensitivity to gas species at flow rates less than 0.130 g/s. The maximum uncertainty was 10 percent at a flow rate less than 0.055 g/s, as seen in figure 6, which is within the manufacture advertised accuracy.

Future Work

The future research on arcjets will involve two power levels: 1-2 kW and 10-26 kW. The low power work will examine the fundamental operation of the thruster to understand the physical phenomenon so that performance and lifetime models can be developed. The Phillips Laboratory is focal point for all high power (26kW) ammonia arcjet work in the USA. Research is underway to increase performance, lifetime and spacecraft integration issues that

must be solved before the high power arcjet is operational.

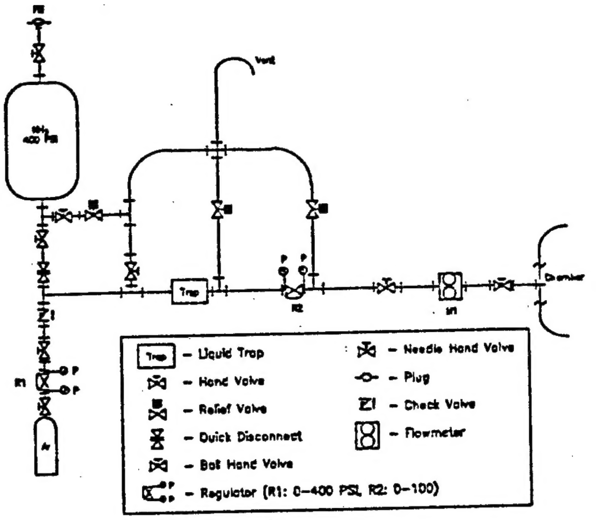

Figure 5
Small Propelant System

The fundamental research uses optical diagnostic techniques, due to high plasma operating temperatures (up to 20,000 deg K), as the primary means to obtain measurements. A continuous wave (CW) Laser Induced Fluorescence (LIF) system is being developed for velocity and temperature measurements of the plasma. Measurements will be made throughout the plume region and eventually inside the expansion nozzle with the objective to better understand the boundary layer and velocity profile losses. Temperature measurements in the interior of the thruster will be taken by interference spectroscopy. Thruster body surface temperatures are obtained using a two-color optical pyrometry system. These measurements are helpful for determining the amount of radiative energy loss from the thruster surface. Also available is a high resolution laser imaging system capable of approximately 10 µm resolution at an observation distance of 1.2 meters. The primary use of the laser imaging system will be to observe erosion of the cathode tip while the thruster is operating.

The performance improvement of the 26kW thruster, being funded by the Air Force will be conducted at the Phillips Laboratory's new facility. This work consists of both numerical modeling and a test matrix of varying constrictor, cathode lengths and nozzle configurations. The numerical modeling will attempt to generate the optimum nozzle expansion for the arcjet using the INCA CFD code and Monte-Carlo software on an Hewlett Packard HP 9000-720 computer system[8]. The 26kW arcjet is also undergoing design changes that will make it more robust to handling, since experimental delays have been encountered due to damage of the fragile refractory materials used in the thruster.

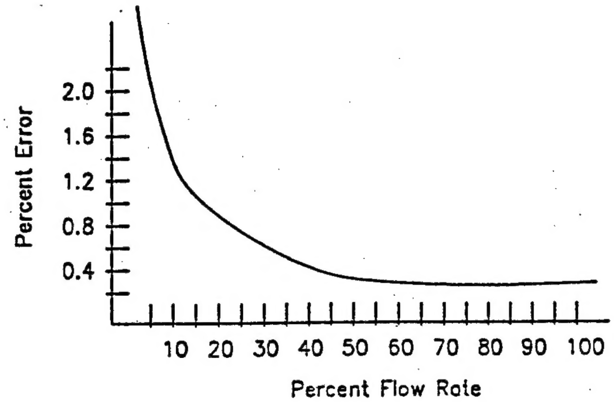

Figure 6
Flow Rate Uncertainty

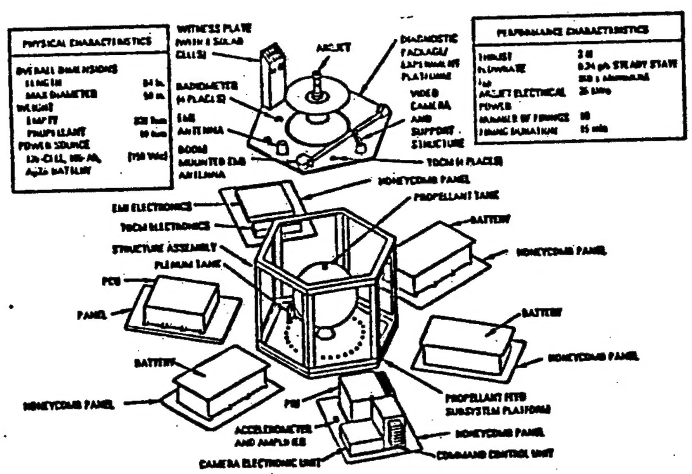

Figure 7
ESEX Flight Unit

Electro Magnetic Interference Experiment

The Phillips Laboratory has a contract with TRW to build a flight qualified arcjet propulsion unit, which will be flown in 1995 as the Electric Propulsion Space Experiment

(ESEX) (see fig. 7). ESEX will fly as part of the Advanced Research and Global Observation Satellite (ARGOS) spacecraft. The objective of the ESEX flight is to measure plume deposition, electromagnetic interference, thermal radiation, and arcjet operation in space. The 1000 watts solar arrays will charge spacecraft batteries, which will supply 15 minutes of power at 26kW to fire the thruster. A 15 minute test firing will assure the thruster is at thermal equilibrium. A total of ten firings are scheduled[9].

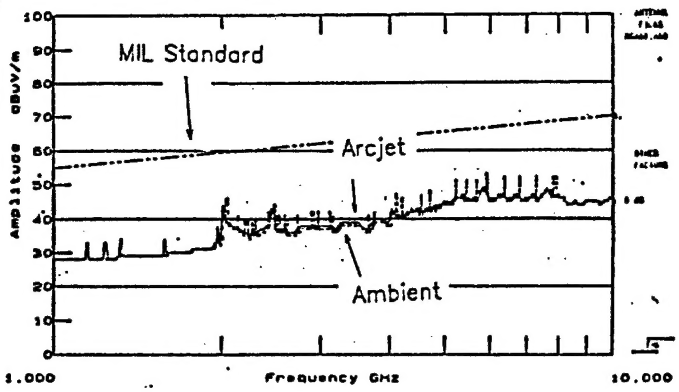

Figure 8
EMI at 1–10 GHz

The ESEX flight will provide a complete EMI profile of the arcjet and all the associated electronics, however there was concern that the arcjet may damage the ARGOS spacecraft and the other flight experiments. To alleviate these concerns, a ground test in the arcjet facility was conducted to measure the thrusters EMI. The test used an Electro-Metrics model EMC-30 spectrum analyzer to take data from 150 kHz to the 10 GHz range.

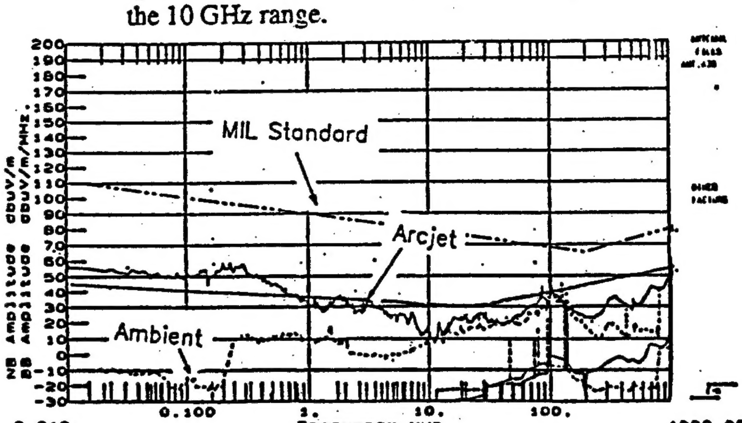

Figure 9
EMI at 0.1–1000 MHz

It is extremely difficult to measure the EMI on earth, since the thruster operates inside a metal vacuum chamber that reflects many frequencies of the EMI as well as interference from local EMI sources. Therefore, the interior of the chamber was covered with anechoic foam and an ambient signal was taken before and after the thruster firing. The antenna was calibrated by placing a transmitter at the arcjet and broadcasting a uniform signal over the frequency range measured.

The arcjet was fired at 15 kW and 26 kW and then compared to the ambient noise present when the thruster was off (see figures 8 and 9). Most of the EMI produced by the arcjet is below the 10 MHz range and is within the limits set for the standard EMI protection of flight hardware[10]. A higher quality measurement will be obtained when ESEX flies in 1995.

Conclusions

The arcjet facility at Edwards AFB is operational and already providing data for the development of the arcjet into space operations. With its three chambers and diverse capabilities, the Phillips Laboratory has become a focal point in the development of electric propulsion.

References

1. S. Castillo, et al, *Dedicated Electric Propulsion Laboratory*, Astronautics Laboratory(AFSC), AIAA 90-2658 (July 90).

2. Jahn, R.G., Physics of Electric Propulsion, McGraw-Hill Publishing Co., New York, NY, 1968.

3. R.J. Cassady, P.G. Linchon, D.Q. King, *Arcjet Endurance Test Program*, AL-TR-90-069, AL, Edwards AFB, Mar 1991.

4. T. Haag and F. Curran, *High Power Hydrogen Arcjet Performance*, NASA Lewis, AIAA -91-2226, June 91.

5. S. Castillo, *Arcjet Facility*, Phillips Laboratory, PL-TR-91-3085, Oct 91.

6. Material Data Safety Sheet, Air Products, 1988.

7. W.D. Deninninger, *30-kW Ammonia Arcjet Technology*, Final Report, Jul 1986-Dec 1989.

8. G.A. Bird, *The G2/A3 Program System User Manual*, Version 1.3, Sep 1988.

9. M. Kriebel and J. Stevens, *30-kW Class Arcjet Advanced Technology Transition Demonstration (ATTD) Flight Experiment Diagnostic Package*, TRW Redondo Beach, AIAA-92-3561.

10. MI-461C.